

PROBABILISTIC STRUCTURAL ANALYSIS COMPUTER CODE (NESSUS)*

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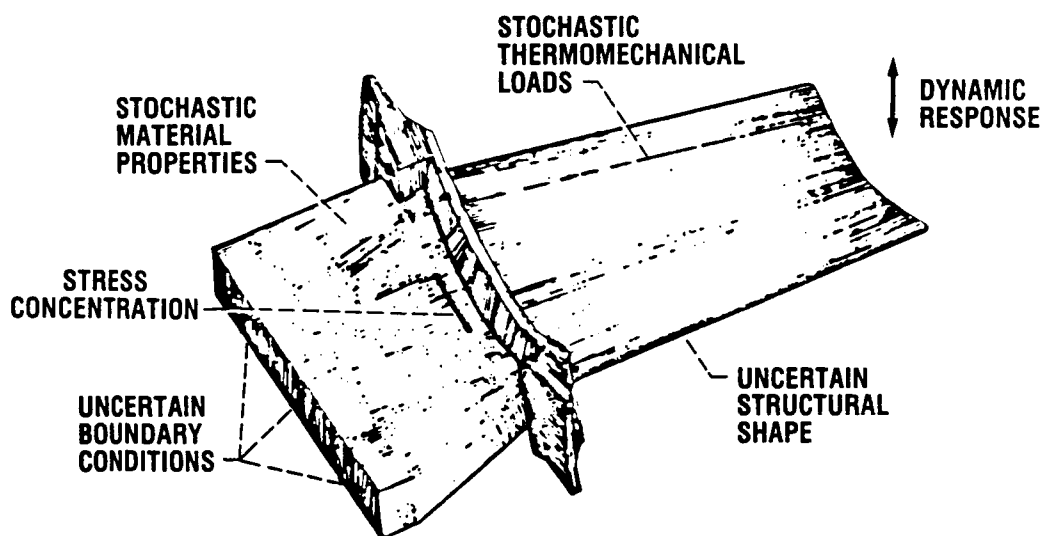
ABSTRACT

In the past, structural design was based on deterministic analysis using known geometry, material properties, loads, and boundary conditions. A safety factor was then used to ensure structural reliability. More recently, probabilistic structural analysis has been developed to analyze the effects of fluctuating loads, variable material properties, and uncertain analytical models especially for high performance structures such as SSME turbopump blades. In the deterministic approach, uncertainties in the response were not quantified and actual safety margin in the design remained unknown. Probabilistic structural analysis provides a systematic method to evaluate structural performance and durability. Probabilistic Structural Analysis Method (PSAM) for Select Space Propulsion System Components is a research and technology program sponsored by NASA Lewis. The objective of this program is to characterize the probabilistic structural response due to the stochastic environments by statistical descriptions. The computer code NESSUS (Numerical Evaluation of Stochastic Structure Under Stress) has been developed by Southwest Research Institute (SWRI) to serve as a primary computation tool for this purpose. The current code consists of three major modules NESSUS/PRE, NESSUS/FEM, and NESSUS/FPI. NESSUS/PRE is a preprocessor which decomposes the spatially correlated random variables into a set of uncorrelated random variables using a modal analysis method. NESSUS/FEM is a finite element module which provides structural sensitivities to all the random variables considered. NESSUS/FPI is Fast Probability Integration method by which a cumulative distribution function (CDF) or a probability density function (PDF) is calculated. Further risk assessment can be continued once the probability distribution function is known.

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UNCERTAINTIES IN THE PROBABILISTIC STRUCTURAL ANALYSIS

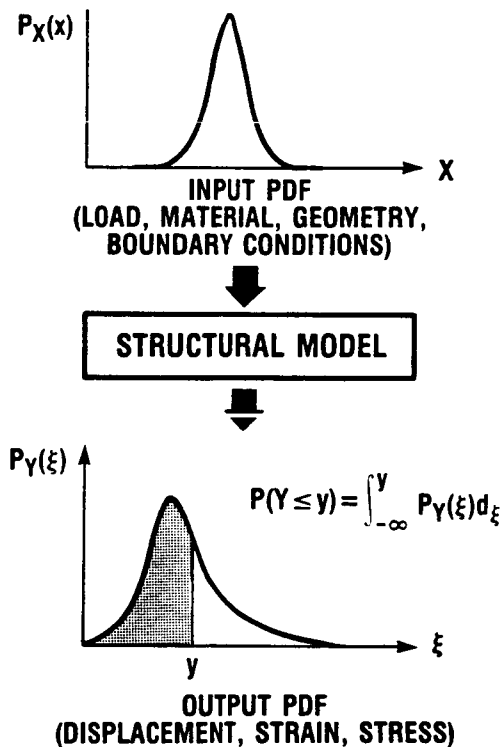
Probabilistic structural analysis requires the uncertainties involved be recognized and quantified. An SSME turbopump blade is subjected to complex mechanical and thermal loads and will be used to illustrate the randomness concerned in the analysis. The dominant loads on the turbine blade are centrifugal force, thermal load, and the differential pressure across the airfoil. Centrifugal force is induced by the rotational blade speed. Since it is difficult to maintain constant rotational speed, the centrifugal force should be defined as a random variable. Random thermal load is due to combustion irregularities which cause a random temperature distribution in the blade. Differential pressure should also be random. Uncertainties in the blade geometry arise during the manufacturing process. The stochastic material properties are caused by the imperfections in the material developed during process. Uncertainty in the temperature distribution also gives another level of material property variation. For the cantilever structure of the SSME blade shown, the boundary is modeled as fully constrained for simplicity. In real structures, flexibility is exhibited at the support due to assembly procedure which should be quantified statistically.



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CONCEPT OF PROBABILISTIC STRUCTURAL ANALYSIS BY NESSUS

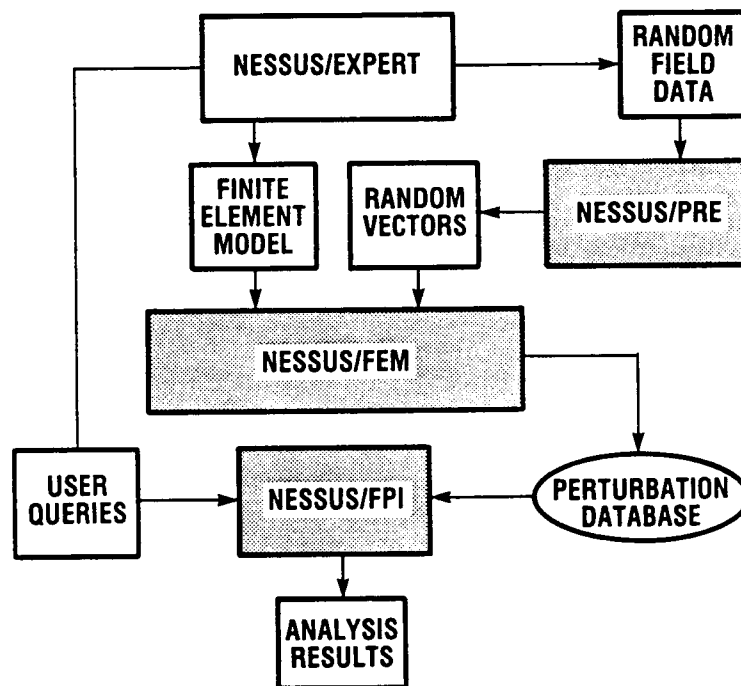
With the loading, material properties, geometry, and boundary conditions defined as random variables, the probabilistic structural analysis is then computed by NESSUS. The structure can be considered as a filter. The response variables, which can be static deflection, strains and stress at one or several locations, or natural frequencies, will also be random and will be described by a cumulative distribution function (CDF) or a probability density function (PDF). For most structures, the analytical distribution function of response can not be obtained and will be evaluated numerically by NESSUS.



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STRUCTURE OF NESSUS

NESSUS (Numerical Evaluation of Stochastic Structure Under Stress) integrates finite element methods technology with probabilistic methods. The code consists of the three major modules shown by the shaded blocks below. NESSUS/PRE analyzes the correlation model. NESSUS/FEM computes sensitivity data. NESSUS/FPI calculates probabilistic results.



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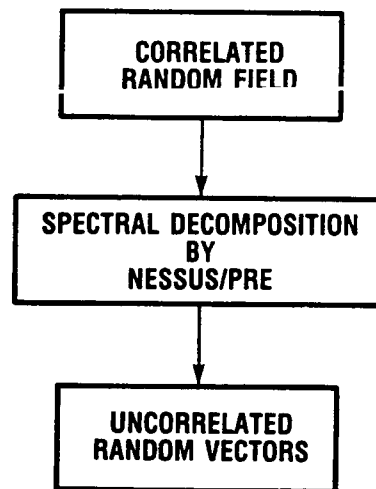
NESSUS/PRE

NESSUS/PRE is a pre-processor used for the preparation of the statistical data needed to perform the probabilistic finite element analysis. It allows the user to describe a spatial domain defined by a set of discrete points, typically corresponding to the nodal points of a finite element mesh. One or more random variable fields may then be specified over this spatial domain by defining the mean value and standard deviation of the random variable at each point, together with an appropriate form of correlation. The current version of NESSUS/PRE limits the treatment of partially correlated fields to fields of Gaussian variables with equal correlation strength in all directions (isotropic correlation). Correlated random variables are decomposed into a set of uncorrelated vectors by a modal analysis. For strong correlation problems, the number of dominant random variables in the set of uncorrelated vectors will be much less than that of correlated random variables. The reduction of the number of random variables will also decrease the computational time required for the analysis. One other reason to have this module developed is that the current FPI code can treat uncorrelated problems only.

ALLOWABLE RANDOM FIELDS

NODAL COORDINATE DATA
NODAL SHELL THICKNESS
NODAL SHELL OR BEAM NORMALS
THICKNESS OF PLANE STRESS ELEMENTS
MODULUS OF ELASTICITY
POISSON'S RATIO
THERMAL EXPANSION COEFFICIENT
MATERIAL DENSITY
ROTATIONAL SPEED
NODAL FORCE VECTORS
ELEMENT PRESSURES/EDGE TRACTION
NODAL TEMPERATURES
ELASTIC BEAM SECTION PROPERTIES
BASE SPRING STIFFNESS
ORIENTATION OF ANISO AXES

NESSUS/PRE

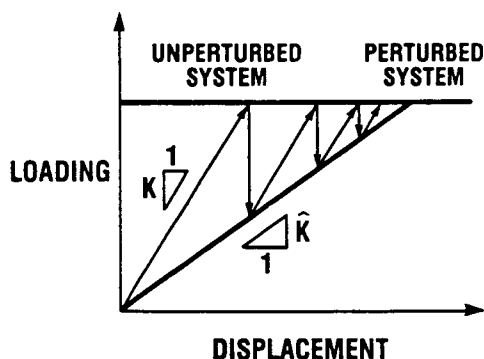


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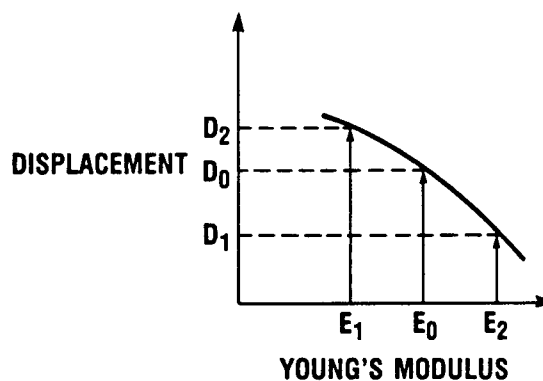
NESSUS/FEM

NESSUS/FEM is a finite element code used for structural analysis and parameter sensitivity evaluation. It also generates a database containing all the response information corresponding to a small variation of each independent random variable. The algorithm used in NESSUS/FPI requires an explicit response function in terms of uncorrelated random variables in order to perform a reliability analysis. In complicated structural analysis problems, response can only be available implicitly through a finite element model. To overcome this difficulty, the response function is estimated numerically. In the figure shown below, the response considered is the displacement D , the uncertainty involved is the Young's modulus E . NESSUS/FEM calculated the displacement D_0 , D_1 , D_2 corresponding to the Young's modulus at E_0 , E_1 , E_2 . D_1 and D_2 are computed by a method akin to the modified Newton nonlinear algorithm. A curve is found to approximate the desired response.

MODIFIED NEWTON ITERATION



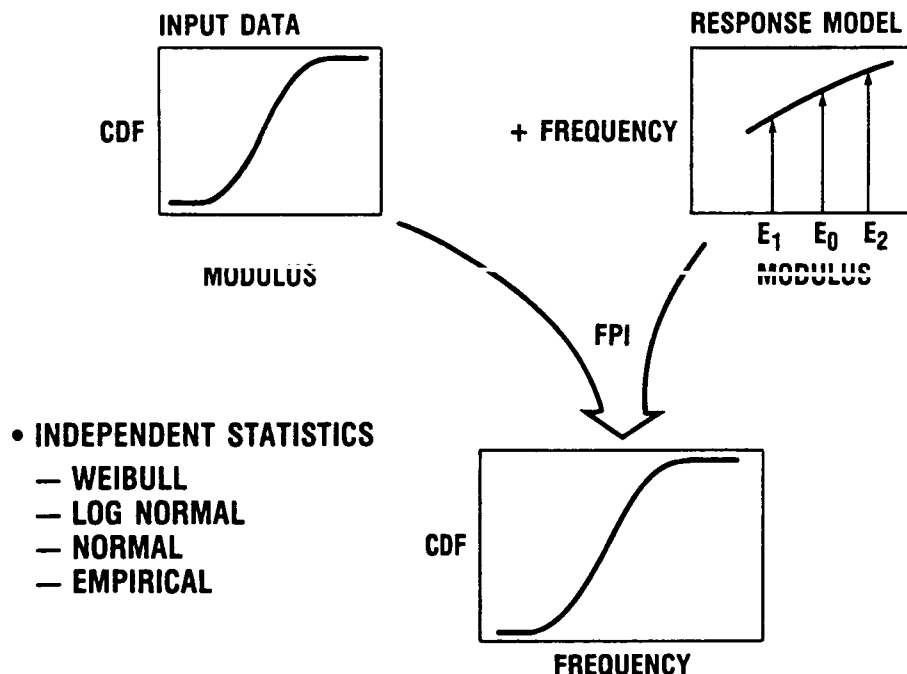
RESPONSE MODEL



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NESSUS/FPI

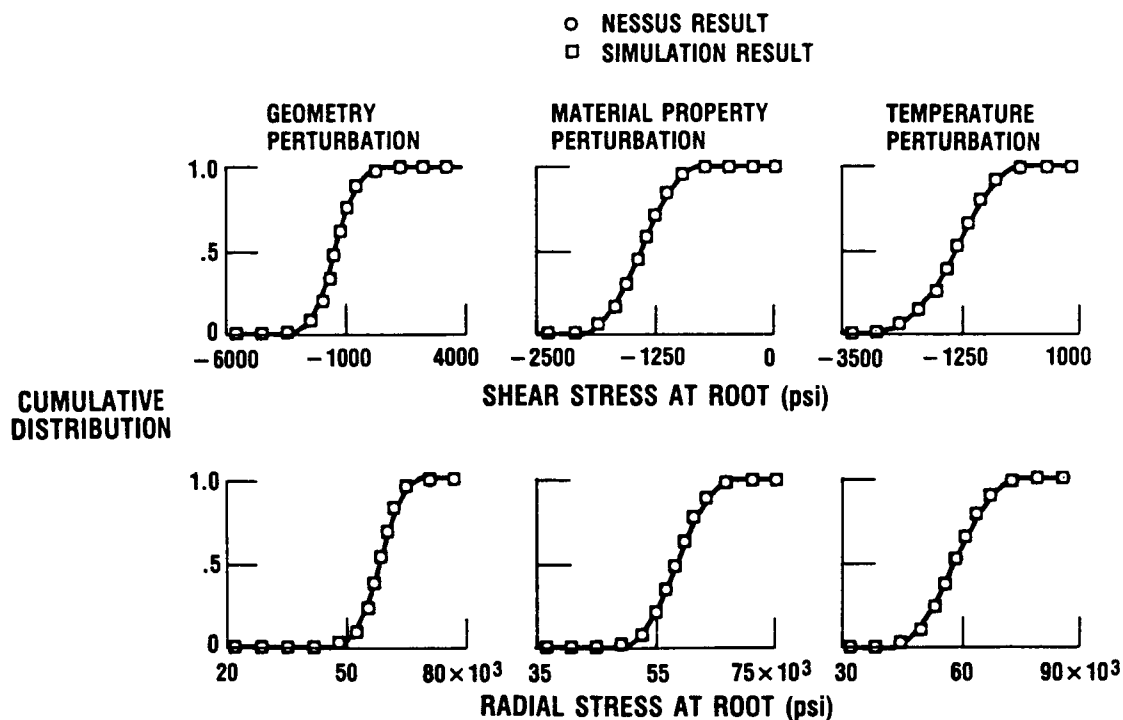
NESSUS/FPI (Fast Probability Integrator) implements an advanced reliability method. This method plays an important role in risk assessment of civil engineering structures. This module extracts data from the database generated by NESSUS/FEM to develop a response or performance model in terms of uncorrelated random variables. The probabilistic structural response is calculated from the performance model. For a given response value, the probability of exceedance at this value is estimated by a reliability method, which treats the problems as a constrained minimization. This step is called a point probability estimate. The cumulative distribution function can be obtained numerically by running FPI at several response values. One alternative for generating the distribution function for any given response is by a Monte Carlo simulation study. However in general, it is very costly. NESSUS/FPI provides a method which not only produces a reliable distribution, but also requires less computing time than that for Monte Carlo simulation, especially in the low probability region.



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NESSUS VALIDATION

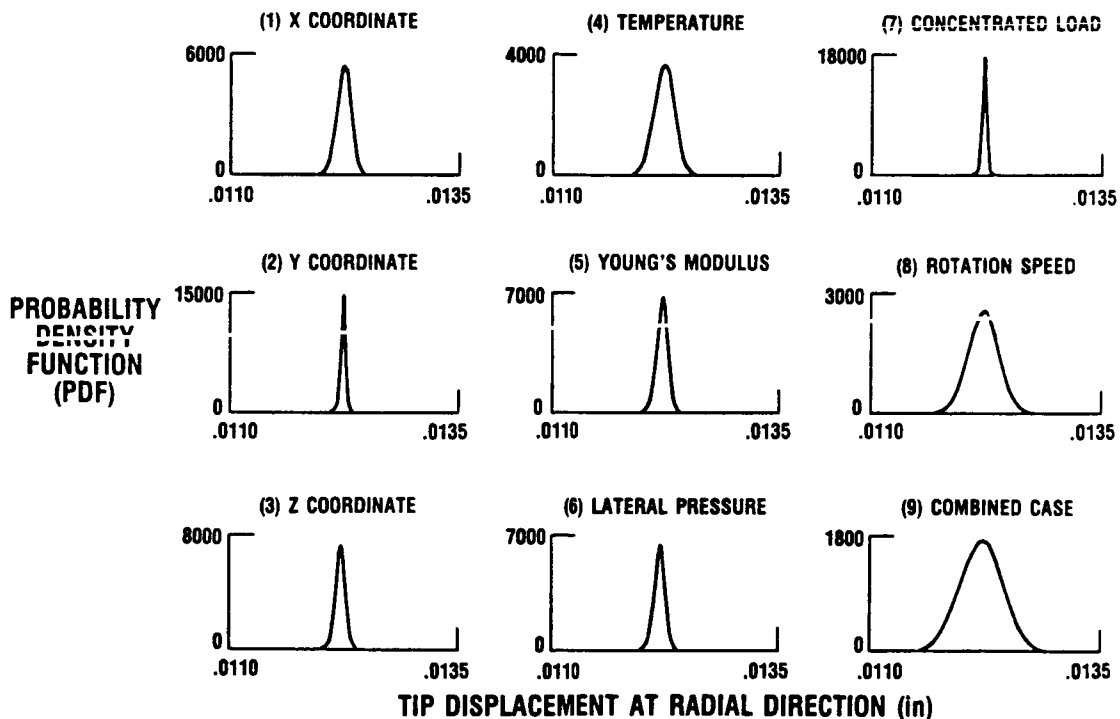
A SSME turbopump blade has been modeled by four node shell elements. NESSUS and Monte Carlo simulation are used to calculate the cumulative distribution (CDF) function. In principal, given an extremely large random sample, the Monte Carlo results will be exact. However, large computing time will be necessary to achieve convergence especially in the low probability region. NESSUS implements an approximation scheme requiring less computing effort. Three validation studies are presented. Nodal coordinates in the radial direction, Young's modulus in each element, and nodal temperatures are assumed to be random for each case. Three hundred sample points are generated by Monte Carlo simulation. In general, the results from two methods agree with each other.



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TURBINE BLADE STUDY BY NESSUS

Because of the severely stochastic launch environment for SSME components, such as a turbopump blade, deterministic analyses cannot be realistic. Examples of probabilistic analyses of a SSME blade using NESSUS are presented. The nodal coordinates, nodal temperatures, lateral pressure, Young's modulus, concentrated loads, and blade speed are modeled as random fields. The response analyzed is the radial tip displacement. Probability density functions for displacement are presented. In the first eight cases, the PDF is generated assuming one random field. The ninth example is the PDF due to the combined effect of these eight random fields. From this study, it can be concluded that rotation speed, nodal temperature, and material properties have more effect on the distribution of radial tip displacement than concentrated loads or y-coordinate perturbation. In the combined case study, NESSUS/FPI also provides sensitivity information on the response for each random variable.



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